THEORETICAL PERSPECTIVE

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1. Introduction

A conference devoted to the center of our Galaxy inevitably draws together astronomers from many different tribes speaking in tongues about what they each know to be truly important. We have heard from stellar dynamicists and users of magnificent infra-red arrays, (who are apparently only here by courtesy of a hole in the dust distribution), from molecular radio astronomers and experts on solar MHD, cosmic ray physicists and those who misguidedly believe that understanding the Galactic center is much easier than solving the mysteries of quasars. The Galactic center can lay claim to being the melting pot of astronomy and so it is quite appropriate that this conference should be held here in Southern California.

Most theorists yearn for the simplicity of a massive black hole surrounded by an orderly axisymmetric distribution of stars and gas. Unfortunately, the observers have demonstrated that the Galactic center is highly complex. This complexity, which dooms most popular colloquia on this topic, has become even more disconcerting since the Townes Symposium. At the start of this conference, I whimsically described the Galactic center as a "three ring circus", but by paying attention to the talks and posters, I think I can count a full Olympian complement of five rings. In addition, there are arms and arches, bars and bridges, clouds and clumps, not to mention a pistol, a thorn and a mouse. My head begins to spin and I doubt if I am alone in this. I suggest that the proceedings contain a lexicon and the editors take it upon themselves to make these terms consistent between the contributed articles.

This contrast between the physical concepts and the phenomenological reality, presents a challenge to theorists. As usual there have been varied responses. To the more austere of my colleagues, the environment at the center of our Galaxy is insufficiently energetic and irretrievably meteorological, and they dismiss it as an unsuitable subject for study. By contrast, other theorists have embraced the subject and turned this complexity to advantage as they realize that they do not have to search far to find some observation that can be attached to their favorite current idea. Of course, neither of these reactions is particularly responsible. It is far preferable to sift through the data and concentrate on drawing secure conclusions about the contents of our Galactic center and, perhaps more importantly, to

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abstract general principles that describe the behavior of stars and gas that can be exported to the interstellar medium and the nuclei of other galaxies. Naturally, all the talks and posters here fall into this third category.

As we have already had several summary talks and indeed one summary of summaries, I have chosen to confine my remarks to two main subjects, black holes and magnetic fields. However, I will list some smaller topics that seem suitable for further study. In the interests of brevity, I shall only list papers in this volume where references to the archival literature can be found.

2. Black Holes

The central issue for a theorist is surely the existence of a massive black hole. Professor Townes, in his stimulating introductory remarks presented the dynamical evidence which has become steadily more precise, that there is a central mass of $\sim 3 \times 10^6 (D/8\text{kpc}) M_\odot$ (McGinn, Lacy, Rieke). Evidence for similar masses has been presented in other nearby galaxies (Phinney, Lee), but of course in no case can we *prove* that a dynamically measured mass is associated with a single collapsed object. Nevertheless, there has been significant observational progress which goes some way towards removing the most serious objections to the naïve massive black hole model.

Traditionally, IR astronomers and radio astronomers have campaigned for their candidates, IRS16 and Sgr A* respectively, to be elected to the highest office in the Galaxy. However, it now seems clear that if there is a black hole, it had better be identified with Sgr A*, because, as reported here, IRS16 comprises at least 5 sub-components that half surround Sgr A* (Becklin, Rieke). Indeed, it is a bit surprising that all of the components of IRS16 are on one side of Sgr A*. Now if each of these sub-components were a star cluster, then they could not co-exist with a black hole as they would be torn apart by tidal stresses. However, these sub-components have similar IR spectra consistent with their being individual ultra-luminous Wolf-Rayet stars (Allen). This disposes of the tidal problem. Furthermore, the 700 km s^{-1} broad helium lines (Lacy) can now be associated with the superposition of the individual stellar winds rather than a large-scale Galactic wind.

Now, as the evolution times of a Wolf-Rayet star lies comfortably inbetween the crossing time and the settling time in the center of the star cluster, we can conclude that the stars must have been formed there out of trapped gas. This, in turn, strongly suggests that there is a compact mass present, heavy enough to create a noticeable depression in the gravitational potential well out to $\sim 10^{17}$cm, i.e. $\sim 10^6 M_\odot$. Perhaps most of the gas accreting towards the center of the Galaxy forms into stars (with the residue being blown away by stellar winds) rather than accreting onto the central black hole (Phinney). The mass loss by the bulge stars $\sim 0.08 M_\odot \text{yr}^{-1}$ (Frogel, Rich) is more than adequate to account for the required gas supply.

A final difficulty with the massive black hole model has been its association with the source of positrons whose annihilation line is observed in the Galactic center region (Lingenfelter and Ramaty). Some of these gamma rays come from an extended source, but another component is reported to be variable and is therefore presumably compact. Now, if these positrons are to be produced by two-photon pair production around a black hole, then the natural length and mass scale indicated is $\sim 10^3 M_\odot$, much smaller than mass suggested dynamically. However, it now appears that the hard X-ray source in the Galactic center is quite distinct from Sgr A*, and so there is less incentive to associate the positrons with a black hole (Skinner, Cook *et al.*).

Attractive though these resolutions of the massive black hole model might be, difficulties remain. Ozernoy has once again reminded us that a low mass black hole is a viable alternative. If the broad helium lines in IRS16 are associated with a wind from the Galactic center then this wind ought to accrete onto Sgr A*. An estimate of the mass accretion rate from the wind onto Sgr A* and a comparison with the known luminosity leads to an upper bound on the mass, again much less than $\sim 10^6 M_\odot$.

Fortunately, the massive black hole interpretation makes a simple prediction - the radial velocities and proper motions of the IRS16 sub-components should be $\gtrsim$ 300km s^{-1} which should be just about measurable (*cf.* Maillard and Gay, Masson *et al.*).

In a different approach to inferring the mass at the Galactic center, Duschl considered the evolution of a hypothetical α accretion disk. He found that generically, the disks become self-gravitating and that mean accretion rates of $\sim 10^{-4} - 10^{-3} M_\odot yr^{-1}$ should ensue, leading to hole masses$\sim 10^6 - 10^7 M_\odot$ over a Hubble time. If accretion rates of this order are the rule then either the current radiative efficency must be very low or the accretion is intermittent and we are now in a low accretion phase (Lee).

3. Magnetic Field

Perhaps the subject that ranks second in general importance is the rôle of magnetic field and this has also been widely discussed. As many of us have discovered, there is a disease called campophobia, or fear of fields, endemic to astronomy. The symptoms of those who are seriously afflicted include denying their existence. I believe that with the discovery of the arched filaments and threads in the Galactic center (Yusef-Zadeh), the evidence that hydromagnetic effects are at work has become overwhelming. The strong polarisation (Inoue *et al.*) and the straightness of these features surely strengthens the case that they are magnetic in origin and makes less plausible the alternative explanations that have been mentioned here, namely edge-on radiative shocks and stellar wakes. We are all magnetohydrodynamicists now! In fact,the polarization observations (Aitken) suggest unusually strong fields in the molecular ring and arms that could be as high as 10 mG, with concomitant pressures of $\sim 10^{-5}$erg cm^{-3}, at least two orders of magnitude above the derived gas presures.

During this meeting, we were treated to four eloquent expositions of hydromagnetic theory. Heyvaerts described a comprehensive MHD interpetation of the arch, threads and the radio structure within Sgr A*. He attributed these features to "coronal mass transients", that is to say hernial tubes of magnetic flux that protude from a central magnetised disk, then twist and reconnect to form isolated closed loops. These loops expand under internal magnetic stresses and move away from the disk. They hit the molecular disk, each other and the magnetized walls of a central chimney (delineated by the Galactic center lobes) where they can reconnect through tearing modes and heat the plasma. A small fraction, perhaps one percent, of the available energy can then be used to accelerate relativistic electrons which in turn emit synchrotron radiation.

Now these processes are almost surely all at work at some level, but Heyvaerts *et al.* go on to attempt to interpret specific features in the radio maps and here I have three concerns. My first worry is whether or not the field inferred in the arch ($\sim 10^{-3}$G) can have derived from a much smaller accretion disk without having exerted an unreasonably large magnetic stress there. Secondly, I wonder if these loops could have floated freely away from the Galactic center when it appears that the whole region, and not just some cylindrical walls, is crossed by straight and so presumably low β magnetic field lines (Killeen and Lo). Finally, I am concerned about the coincidence of finding a retrograde molecular cloud at the intersection of the arched filament with the walls. It would seem more likely that it is an unrelated feature along the line of sight.

Benford presented a quite different but no less stimulating interpretation of some of these radio features. In his model, the molecular cloud is responsible for exciting a small bundle of filaments by driving field-parallel currents along them. Here my concern is to wonder if the unusually small transverse sizes of these filaments, which are dictated by his microphysical model, really make sense. Would not a small level of Alfvén turbulence cause the field lines to wander and destroy the integrity of the filaments?

Shibata proposed three mechanisms for forming the Galactic center lobes (Sofue). They may have been formed by impulsively twisting an initially uniform field threading a disk. Alternatively, they could be made by setting off an explosion (perhaps a starburst) within an originally uniform magnetic field. Finally, they could be the non-linear development of a Parker instability. Observations of other galaxies should help to decide if these lobes are such transitory features as all these models demand, or whether they are actually delineating some quasi-stationary outflow. A further nagging doubt is whether or not less well mapped longitudes of our Galaxy exhibit similar features. If they do, then this would imply that the structures in the Galactic center are not directly related to a central energy source.

Finally, Rosner made the observation that the straight filaments in the radio arc appeared to pass right through the disk and drew a far-reaching conclusion, namely that the Galactic field had odd rather than even symmetry. Now the importance of this is that disk dynamos would be expected to generate quadrupolar (or higher multipolar) fields, whereas a dynamo associated with the halo could be dipolar (if the field can penetrate the disk). Now, if such a field is generated in a more active nucleus then it could be convected inwards by inflowing gas in an accretion disk and thereby help to extract the angular momentum and perhaps collimate the outflowing jets. Galactic halo dynamos clearly merit further study.

In spite of all these differences in detailed interpretation, we should not lose sight of the fundamental discovery that extremely "low beta" plasmas can exist in the absence of solid bodies. Therefore, by definition, these fields exert a controlling influence on the dynamics of the gas that they thread.

4. Future Prospects

Let me conclude by listing a few additional theoretical issues that seem ripe for further study.

4.1 GRAINS

The measured infra-red polarization of 8 percent (Aitken) and the equally impressive derived magnetic field of 10mG should stimulate further studies of grain magnetic moments and the quest for more powerful alignment mechanisms than that of Davis and Greenstein.

4.2 PARTICLE ACCELERATION

The inferred non-thermal particle distribution function in the arched flaments is unusually flat for a synchrotron source and is dominated by high energy particles (*cf.* Lesch *et al.*). Have we identified the correct emission mechanism? If we have, could we be observing particle acceleration by electrostatic fields localised to reconnection regions or even double layers rather than shock fronts as now usually suggested? If not, can collective effects, similar to those associated with solar radio bursts, be responsible?

4.3 STELLAR DISRUPTION

What happens to stars as they pass by a massive black hole (Phinney, Lee)? Will most of the tidally stripped gas be so loosely bound that it can be easily expelled? Perhaps the dynamical aspects of this problem are susceptible to treatment by the increasingly popular and sophisticated smooth particle hydrodynamic codes that are being developed.

4.4 INTERPRETATION OF RADIO FEATURES

The radio arms and the bar are widely associated with the inner edge of the circum-nuclear disk and gas streams falling in from it. The velocity data is now impressively good and can be fit to parabolic trajectories (Serabyn). Yet this model pre-supposes that the gas is dropped from a fixed platform rather than one that is itself orbitting about the central mass. Does this make a difference? Furthermore, do the outward extensions of the arms (van Gorkom) indicate that the infall starts from outside the disk?

4.5 ASTROCHEMISTRY

We expect the Galactic center to be a place of enriched heavy element abundances (Frogel, Rich). What are the elemental and isotopic abundances in the circum-nuclear disk (Genzel, Wannier)? Is there any way that we can relate these to the stellar initial mass function and its subsequent evolution?

4.6 DISTANCE TO THE GALACTIC CENTER

The water maser sources (Gwinn) provide one of the most promising methods for securing the distance to the Galactic center (*cf.* Reid, Cohen *et al.*). However, the method contains an implicit assumption that the emission is isotropic which ought to be tested.

4.7 DYNAMICS OF THE CIRCUM-NUCLEAR DISK

Genzel has argued that gas pressure is insufficient to maintain the thickness of the circum-nuclear disk. A similar problem exists in the Seyfert galaxy N1068 (Phinney). Perhaps in both instances, the disk is thickened as a consequence of magnetic stresses. Can such a configuration to be stable?

4.8 INTERSTELLAR SCATTERING

Sgr A* has an angular size that increases quadratically with wavelength, as would be expected if it were broadened by interstellar scattering (Lo). The long term variability is also attributable to refractive scintillation (Zhao *et al.*). However, several background extragalactic sources have been found close the Galactic center (Backer, private communication). This implies that if scattering is responsible, then the screen must be very close to the source, thereby diminishing its effectiveness. Suppose, for example, that the scattering originates in the torus at a distance of order 3pc from the source. In order to broaden the image to the observed diameter of 1" at λ30cm, the plasma would have to scatter the rays through an angle $\sim 1°$. Now the inferred gas density in the emitting clumps within the torus is $\sim 10^5 cm^{-3}$ (Genzel) and it turns out that the plasma would have to have something like order unity density fluctuations on length scales of $\sim 10^{12}$cm, (or somewhat lower amplitudes on even smaller scales), a far higher level of turbulence than that to which we are accustomed in the general interstellar medium. In addition, if the slow variation is refractive in origin the gas must contain large density fluctuations on length scales up to $\sim 10^{17}$cm which change with a speed $\gtrsim$ 1000km s^{-1} larger than the observed rotational velocity of the gas. Perhaps there is a two phase medium with dense clumps of cold gas embedded in low β plasma characterised by a large Alfvén speed. In any case it will be well worth trying to reconcile the physical conditions in the circum-nuclear disk indicated by the line observations with those suggested by scattering models.

5. Coda

This is the fifth Galactic Center conference to have been held in recent years. At the four that I have attended, I have had the distinct impression that theorists are the poor relations of the subject, always trailing behind observers armed with rapidly improving techniques and being intimidated by an abundance of ill-digested morphological and spectroscopic results. However, the infra-red and radio observations reported here now seem to be forcing the issue on the two most far-reaching questions, the existence of a black hole and the rôle of magnetic field. I suspect that we will soon be able to agree that strong gravitational and magnetic fields are present in our essentially dormant nucleus. It will then be hard to doubt that these same ingredients are actively at work in quasars, Seyferts and radio galaxies.

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